Linking Aerosols to Cloud Ice Nucleation Parameterizations in Thompson Microphysics

by

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1. Introduction

In the aerosol aware microphysical scheme described in Thompson and Eidhammer (2014, hereafter referred to as TE14), both cloud droplet activation and ice nucleation is dependent on aerosol number concentration. Several sensitivity tests were conducted for droplet activation of water friendly aerosols (NWFA) in TE14. Here we report on some sensitivity tests and changes done for the ice nucleation and droplet freezing by the ice friendly aerosols (NIFA). Further, we are made aware that simulations conducted by NOAA Global Systems Division (GSD) with TE14 show that there are too few or too thin high ice clouds. We report on suggested changes to the homogeneous freezing of deliquescent aerosols to improve the prediction of high ice clouds. First, the different cloud ice nucleation/freezing parameterizations in the aerosol aware microphysical scheme are briefly described. Then we describe and discuss 4 suits of tests: 1) tests of the heterogeneous nucleation parameterization, 2) tests with changes to dust concentration (NIFA), 3) tests with changes to NIFA and cloud droplet freezing parameterization. 4) tests of homogeneous freezing of deliquescent aerosols.

2. Cloud ice nucleation parameterizations

2.1. Heterogeneous ice nucleation:

In the regular Thompson microphysics (Thompson et al. 2008), heterogeneous deposition ice nucleation is accounted for by following Cooper (1986), which is solely temperature dependent. Droplet freezing (or immersion freezing) is accounted for by following Bigg (1953), where freezing is dependent on temperature and the volume of droplets, in which larger droplets freeze before smaller droplets. This is to account for a higher chance of at least one ice nuclei (IN) in larger droplets than in smaller droplets, due to many small droplets being collected by larger ones.

In the aerosol aware microphysics scheme described in TE14, there is an option for heterogeneous ice nucleation to be dependent on the number, and/or surface area of "ice friendly" aerosols (NIFA). These aerosols are mainly assumed to be mineral dust particles, since mineral dust particles are considered to be the most active IN. The IN dependent deposition nucleation (below water saturation) follows the parameterization by Phillips et al. (2008), while immersion freezing (above water saturation) follows the parameterization by DeMott et al. (2010). The freezing of existing droplets, following Bigg (1953) is still included in the microphysical parameterization, but now the NIFA concentration changes the ''effective temperature'' and freeze more water drops when more NIFA are present, and fewer with lower NIFA concentration. For each order of magnitude the NIFA changes, the effective temperature of freezing of droplets changes by one degree.

2.2. Homogeneous freezing of deliquescent aerosol particles

Deliquescent aerosols can freeze homogeneously at temperatures below about -35 °C. In TE14, the parameterization presented by Koop et al. (2000) is used to freeze NWFA. This parameterization is dependent on the temperature and relative humidity. Note that the freezing rate as calculated with Koop et al. (2000) is reduced by a factor of 100 based on research by Knopf and Rigg (2011).

In the current scheme in TE14, homogeneous nucleation of deliquescent aerosol are only allowed if there are less than 0.1 L^{-1} existing hydrometeors, and if no heterogeneous nucleation has occurred in the current time step. This limit was included to ensure that the cloud ice crystal concentration would not be too high from many homogeneously formed ice crystals.

We note that in the original Thompson et al. (2008) microphysical scheme, there is no explicit homogeneous freezing of deliquescent aerosols. However, the Cooper parameterization predicts high number of ice crystals at low temperatures, thus, implicitly homogenous freezing could be considered as being accounted for in the Cooper parameterization.

3. Updates to TE14 and sensitivity tests

Fan et al. (2014) conducted a study of aerosol impacts on California winter clouds, looking both at cloud condensation nuclei (CCN) and IN from the CalWater 2011 campaign. We have set up the same case to test the ice nucleation/freezing parameterizations in the aerosol aware microphysical scheme. In this report we describe some changes done to the TE14 and numerous sensitivity tests conducted. More direct comparison with observations and Fan et al. 2014 will be conducted later.

The case is run from 00 UTC February 15 to 00 UTC February 17, 2011. We use WRF 3.6 and the simulations are set up with 3 by 3 km horizontal resolution, and 72 vertical layers. The domain is illustrated in Figure 1. We use the unified Noah land surface model, and the Rapid Radiative Transfer Model (RRTM-G) for both short and long wave radiation. Further, we use the version of Thompson microphysics where the effective radius of all hydrometer species is calculated in the Thompson microphysical scheme and used in RRTM-G.

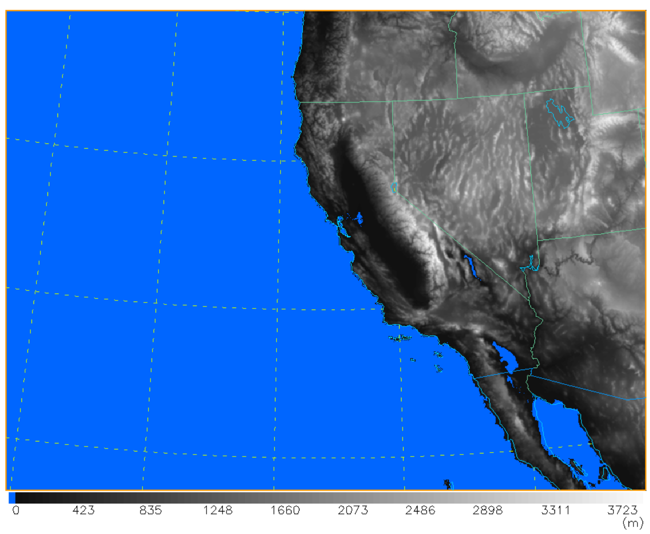

Figure 1: Modeling domain

3.1. Test suite 1: Heterogeneous nucleation

A few updates to the scheme as described in TE14 are implemented. First, the immersion freezing parameterization is dependent on the number of all particles larger than 0.5 micrometer in diameter (DeMott et al. 2010, DM10). However, the NIFA are assumed to be mainly dust particles. DeMott et al. (2015, DM15) presented a new ice nucleation parameterization for dust, which is implemented into the aerosol aware microphysics scheme. This parameterization is in the same form as the parameterization presented in DM10 but with different dependence on temperature. Further, a small error in the air density correction of NIFA in TE14 was found and corrected. These changes are now incorporated for the release of WRF v3.7.

Figure 2 shows the results of Test suite 1. Here the average cloud ice number concentration, cloud ice water content (CIWC, snow water content is excluded) and liquid water content (LWC) over the entire domain (minus 10 grid-points along the domain edges) from hours 3-12 of the simulation are plotted. In all figures presented in this report we include the predictions based on the Cooper parameterization (i.e. same as non aerosol-aware scheme) as a reference. The Cooper parameterization predicts a higher number of ice crystals and cloud ice water content at the colder temperatures (< -30 °C) compared to NIFA dependent ice nucleation/freezing, while at the warmer temperatures there is little difference between Cooper and NIFA dependent ice nucleation. The red curve shows the current DM10 parameterization used in TE14, while the blue curve shows the new DM15 parameterization, based on dust particles. The new DM15 parameterization predicts a few more ice crystals and slightly higher ice water content at the warmer temperatures compared to DM10 and a few less ice crystals at temperatures between -30 and -45 °C. Finally, we note that the liquid water content, shown in Figure 2c, does not vary much between the difference different simulations.

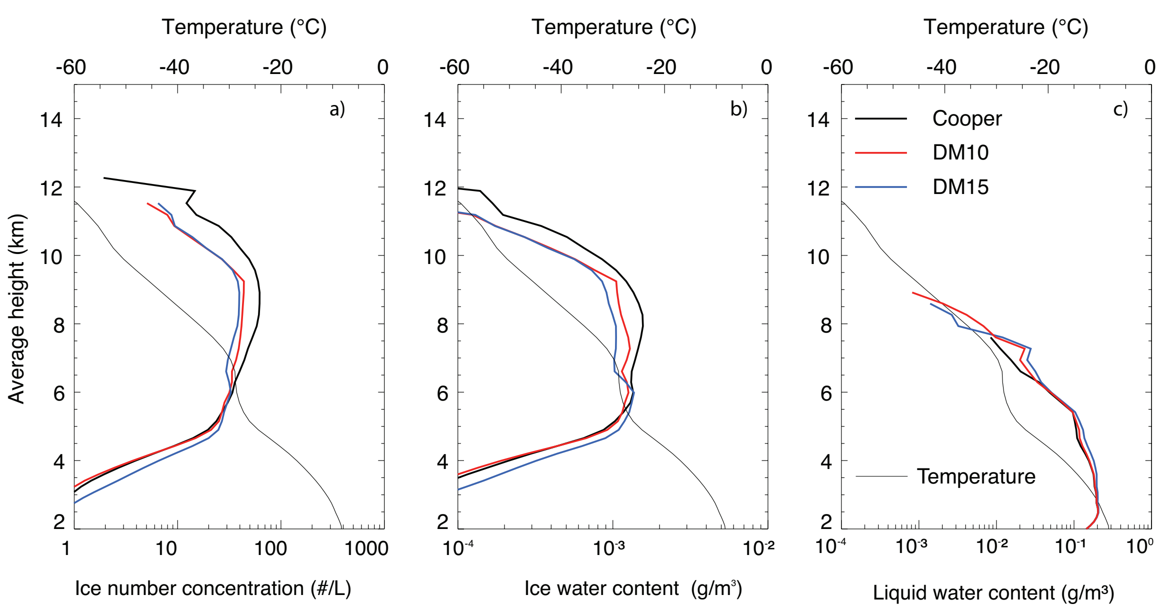

Figure 2. Test suite 1: Results from 12 h simulation. Results are averaged over the entire domain. a) Ice number concentration. b) Cloud ice water content. c) Liquid water content. Thin black line represents the average temperature. The black thick line represent simulation with the Cooper parameterization, red line with DeMott et al. (2010) parameterization and blue with DeMott et al. (2015) parameterization.

3.2. Test suites 2 and 3: Changes to NIFA concentrations

By changing the concentration of available ice nuclei, (i.e. NIFA), the resulting number concentration of ice crystal changes. However, due to the different types of ice formation (heterogeneous and homogenous nucleation/freezing) and other loss processes, the relationship between IN and ice crystal concentration is not necessary linear. We conducted a test with changing the NIFA concentration by factors of 0.1 and 10, and compared the results with simulations with the original NIFA concentration (Test suite 2). The results are shown in Figure 3. Note that these tests are conducted with the original TE14 scheme, where DM10 is used for heterogeneous nucleation. At the lower levels (warmer temperatures > -25 °C) there are almost no changes in ice crystal number concentration between the different simulations. At higher altitudes (lower temperatures), the high dust cases produced a decrease in ice number concentration. This is most likely due to competition between heterogeneous and homogeneous freezing. The same trend is seen in the cloud ice content.

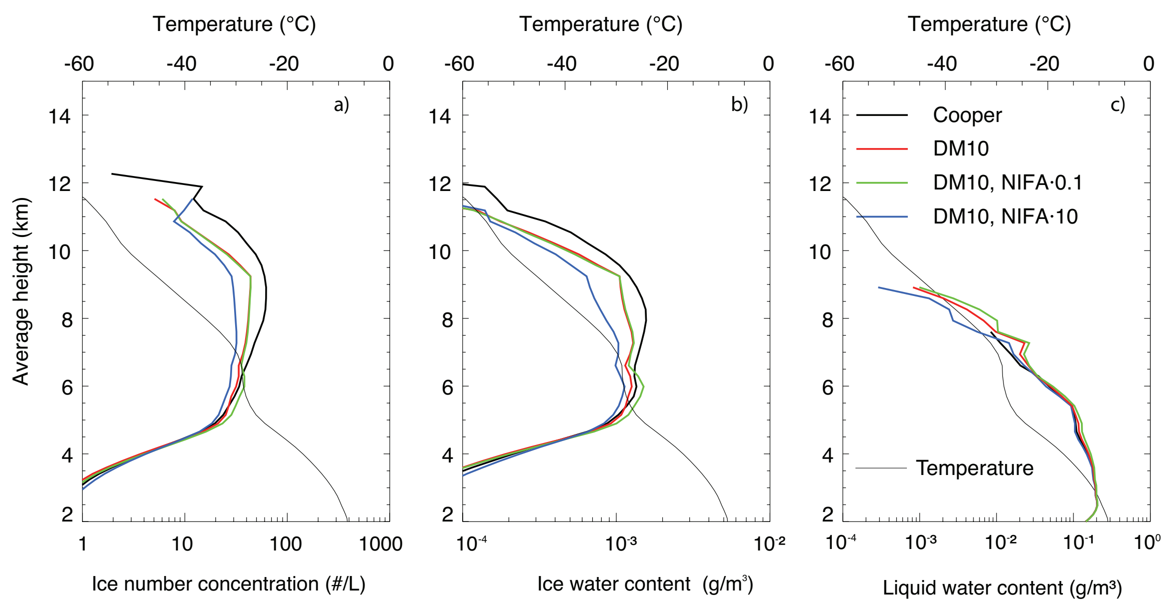

Figure 3. Test suite 2: Same as Figure 2, but for NIFA sensitivity tests. Here the red line represent the default NIFA concentration, green line represents NIFA concentration reduced by a factor of 10 and blue line represents NIFA concentration increased by a factor of 10.

We note that by including the heterogeneous droplet freezing (Bigg) and the DM15 parameterization, we might be double counting heterogeneous ice nucleation. We therefore tested the scheme without the Bigg droplet freezing. Figure 4 shows the ice crystal concentration when the Bigg freezing is excluded, for the 0.1·NIFA, NIFA and 10·NIFA cases (Test suite 3). Now there is a clear difference between the different assumed NIFA concentrations. For example at 5 km (~-25°C), the ice crystal concentration varies between 8 L^{-1} to 30 L^{-1}, which is much higher than seen in Figure 3. This variation of ice crystal concentration also has an impact on the liquid water content with higher LWC in the low NIFA cases at warmer temperatures (the difference is about a factor of 1.5).

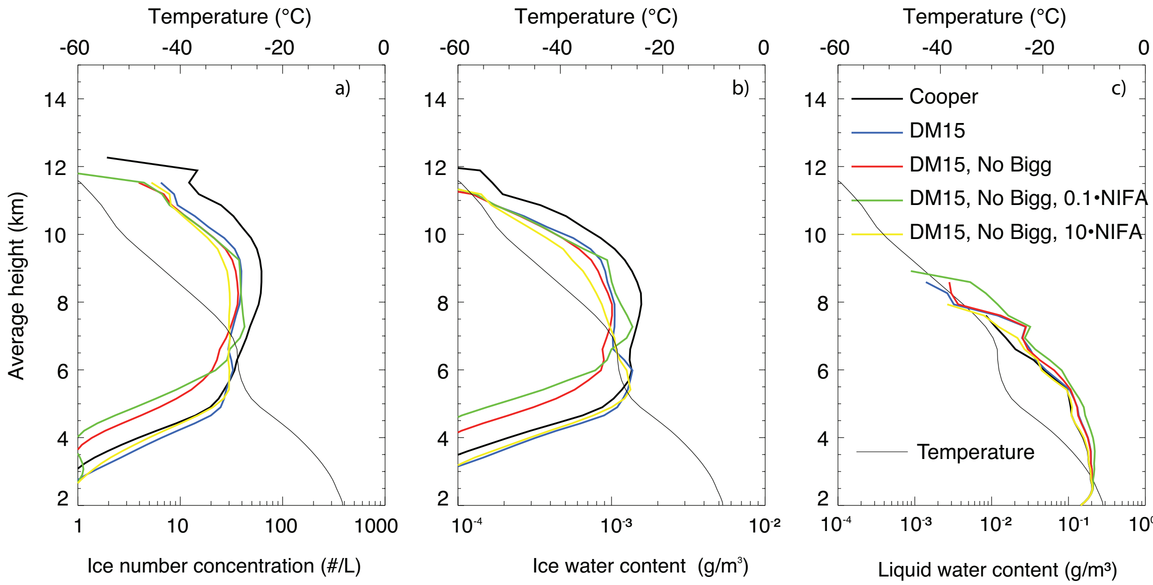

Figure 4. Test suite 3: Same as Figure 2, but for NIFA sensitivity tests, and no droplet freezing following the Bigg parameterization. Here the blue line represents the default NIFA concentration, red line has no Bigg freezing, and green line has reduced NIFA concentration and without Bigg freezing, yellow line has increased NIFA and without Bigg freezing.

Aircraft observations from CalWater on February 16, 2011 showed that the ice crystal number concentration was about 1- 5 L^{-1} in the heights between 1 and 4 km above ground (Fan et al. 2014). This is comparable with our results when the Bigg freezing is excluded for the NIFA and 0.1·NIFA cases. More detailed comparisons are needed, but as a first order comparison, the results are reasonable. A proposed next step is to link the DM15 freezing to the Bigg freezing and let the largest rain or droplet particles freeze first. In this case, we would pay specific attention to the resulting LWC, to determine if changing the Bigg droplet freezing would result in clouds with worse LWC forecasts.

3.3. Test suite 4: Homogeneous freezing of deliquescent aerosols

While incorporating the homogeneous nucleation of deliquescent aerosols by Koop et al 2000, a limiter on how many new ice crystals could from was included into the first version of the microphysical code. No new homogeneous nucleation could occur if the existing ice crystal concentration was higher than 0.1 L^{-1}. However, based on reports from NOAA GSD simulations using RAP and HRRR, there were indications that TE14 produced too few or too thin high ice clouds. Therefore we tested this limit by allowing homogeneous nucleation to occur even if there are existing ice crystals present (Test suite 4). The results are shown in Figure 5. When there are no limits on homogenous freezing, the ice cloud number concentration and IWC increases. However, the IWC and ice number concentration does not exceed what is predicted by the Cooper parameterization, which is subjectively thought to produce too much ice at cold temperatures. The elimination of the restriction on homogeneous freezing of deliquescent aerosols has now been included in the new WRF v3.7.

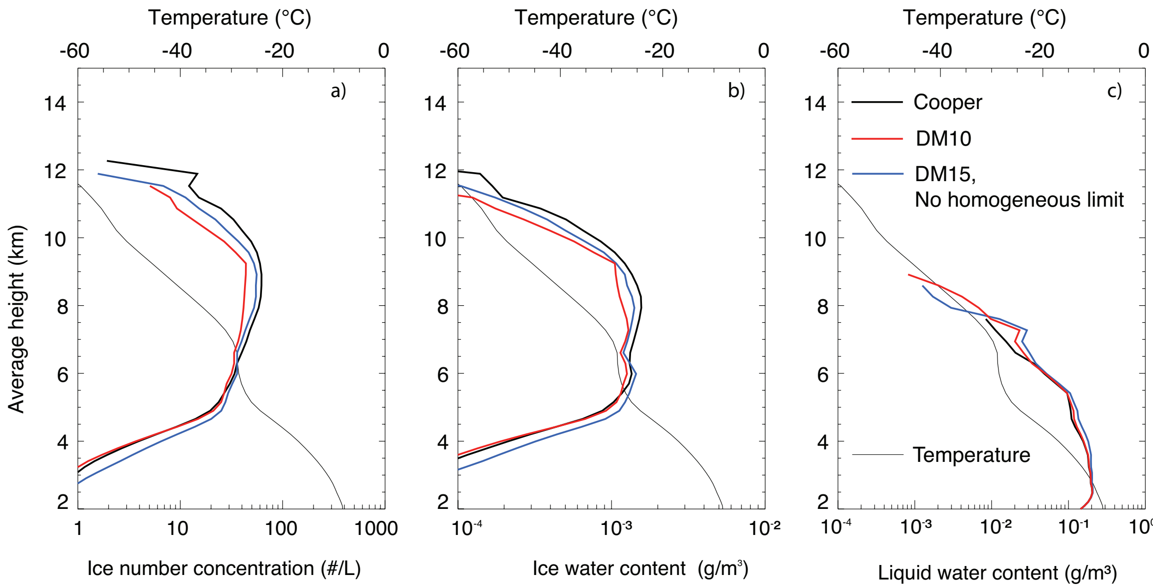

Figure 5. Test suite 2: Same as Figure 2, but for sensitivity tests of homogeneous freezing of deliquescent aerosols. Here the red line represents the current WRF v3.6, (with DM10) and blue curve represent changes made for WRF v3.7 (DM15 and removed limit for homogeneous freezing of deliquescent aerosols).

4. Summary and Recommendations

Based on the sensitivity tests conducted here, together with new published research, we conclude with a few recommendations for changes in TE14. The DM10 parameterization has been updated to DM15. A small density correction bug has been fixed. The resulting changes in ice crystal concentrations are not large (Figure 2), but a more correct relationship between dust and IN is now used. To increase the cloud ice at cold temperatures, we suggest removing restriction on homogeneous freezing of deliquescent aerosols. Test suites 4 (Figure 5) show that this approach would increase high ice clouds. These changes are included in WRF v3.7.

With the ice nucleation parameterizations in TE14, changes to NIFA concentration do not have a large impact on cloud ice crystal concentration at relatively warmer temperatures. This is most likely due to the inclusion of droplet freezing following Bigg (1953). It is suggested to investigate inclusion of a direct link between IN concentration and the droplet freezing following Bigg in future work.

Finally, in the Appendix we show 6-hourly GOES infrared satellite images of cloud top temperatures (top-left) for the case simulated here. We also include synthetic satellite images from WRF results, using the original Cooper parameterization (top-right), the original WRF v3.6.1 aerosol-aware results following TE14 (lower-left), and the final results after making all suggested code changes (lower-right).

Appendix

00 UTC:

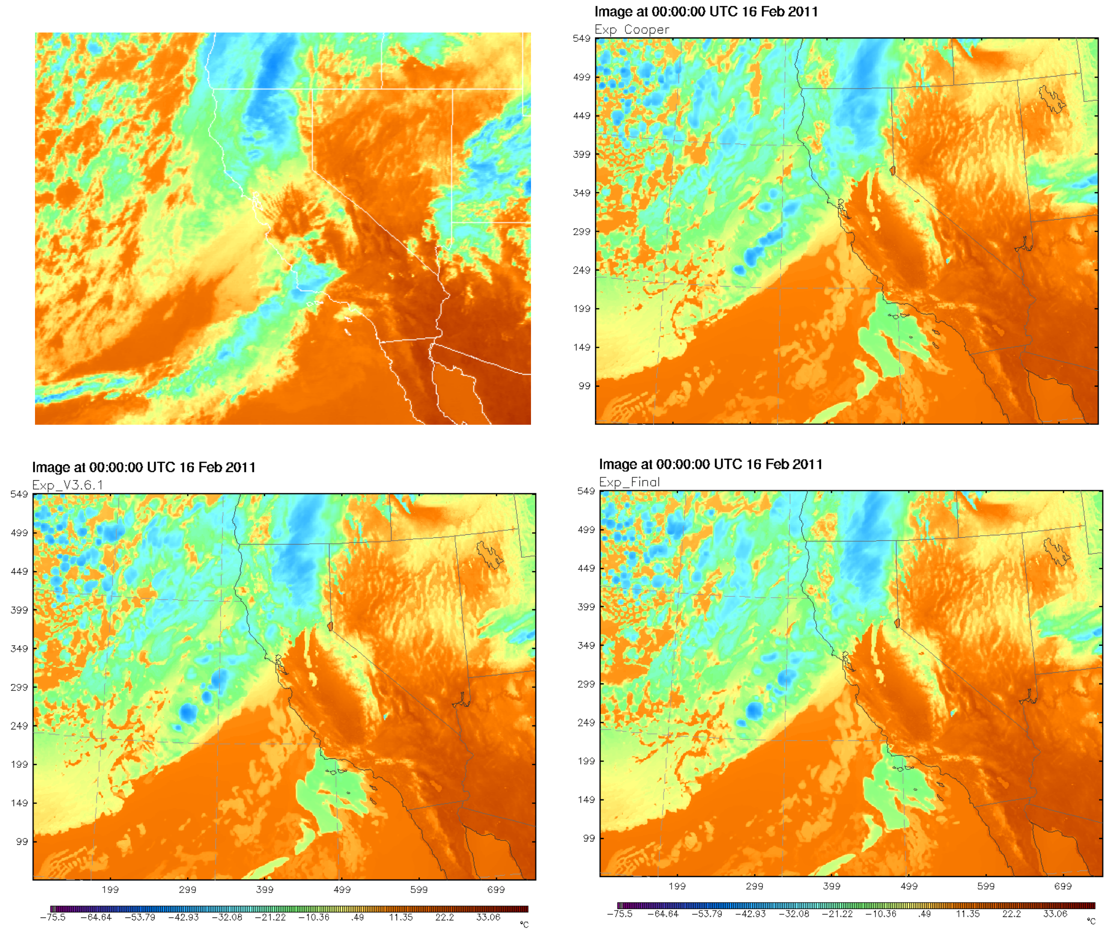

Figure A-1: 0000 UTC 16Feb 2011. Cloud top temperature. Top-left: Infrared satellite GOES image. Top-right: Synthetic infrared satellite image with original Cooper parameterization. Lower-left: Synthetic infrared satellite image with original WRF v3.6.1 aerosol-aware scheme. Lower-right: Synthetic infrared satellite image new recommended code changes.

6 UTC

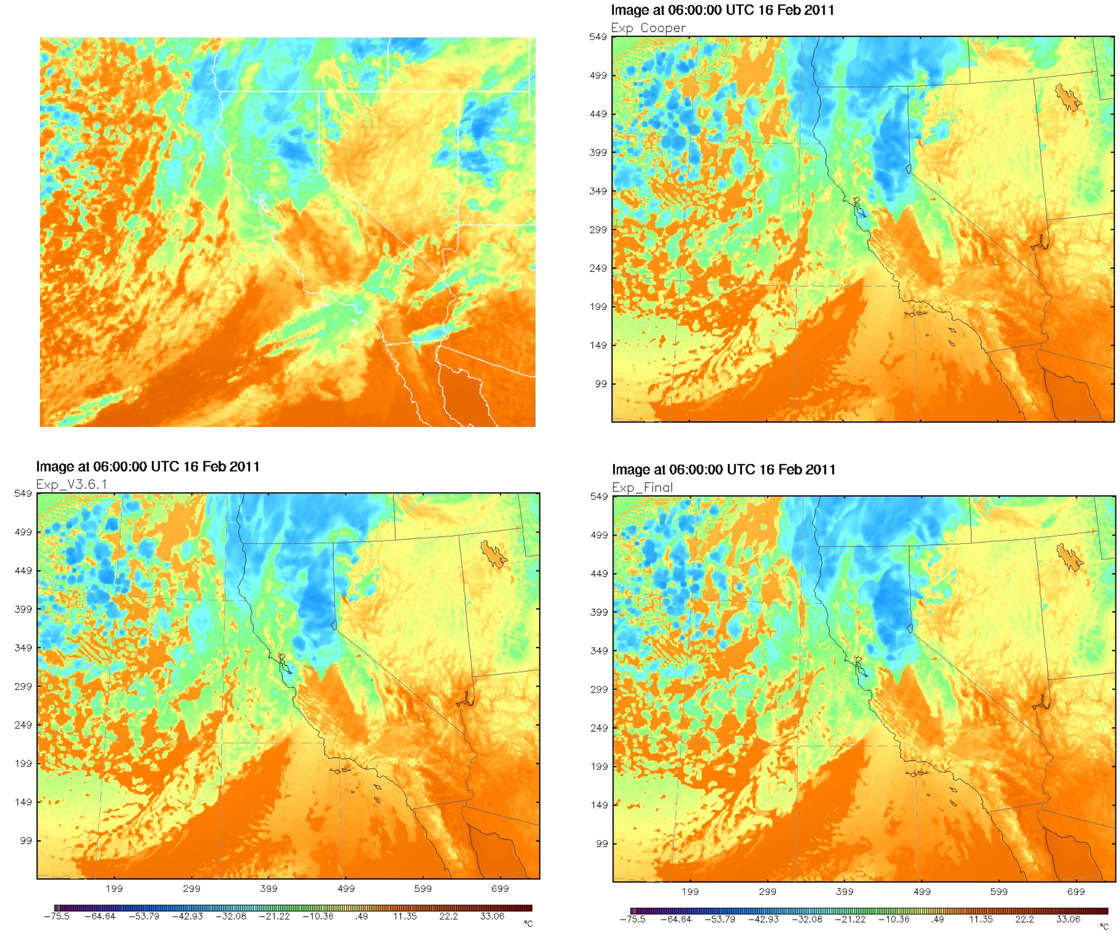

Figure A-2: Same as Figure A-1, 0600 UTC 16Feb 2011

12 UTC

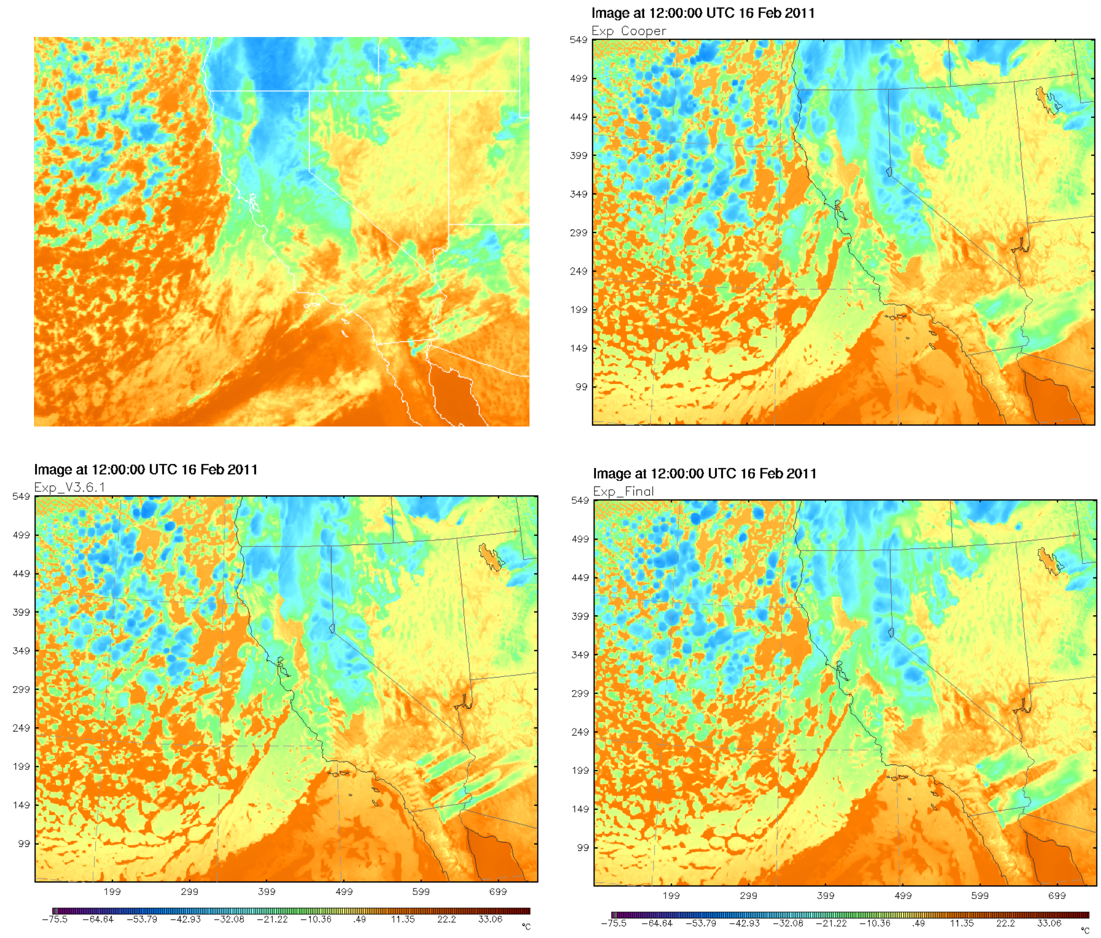

Figure A-3: Same as Figure A-1, 1200 UTC 16Feb 2011

18 UTC

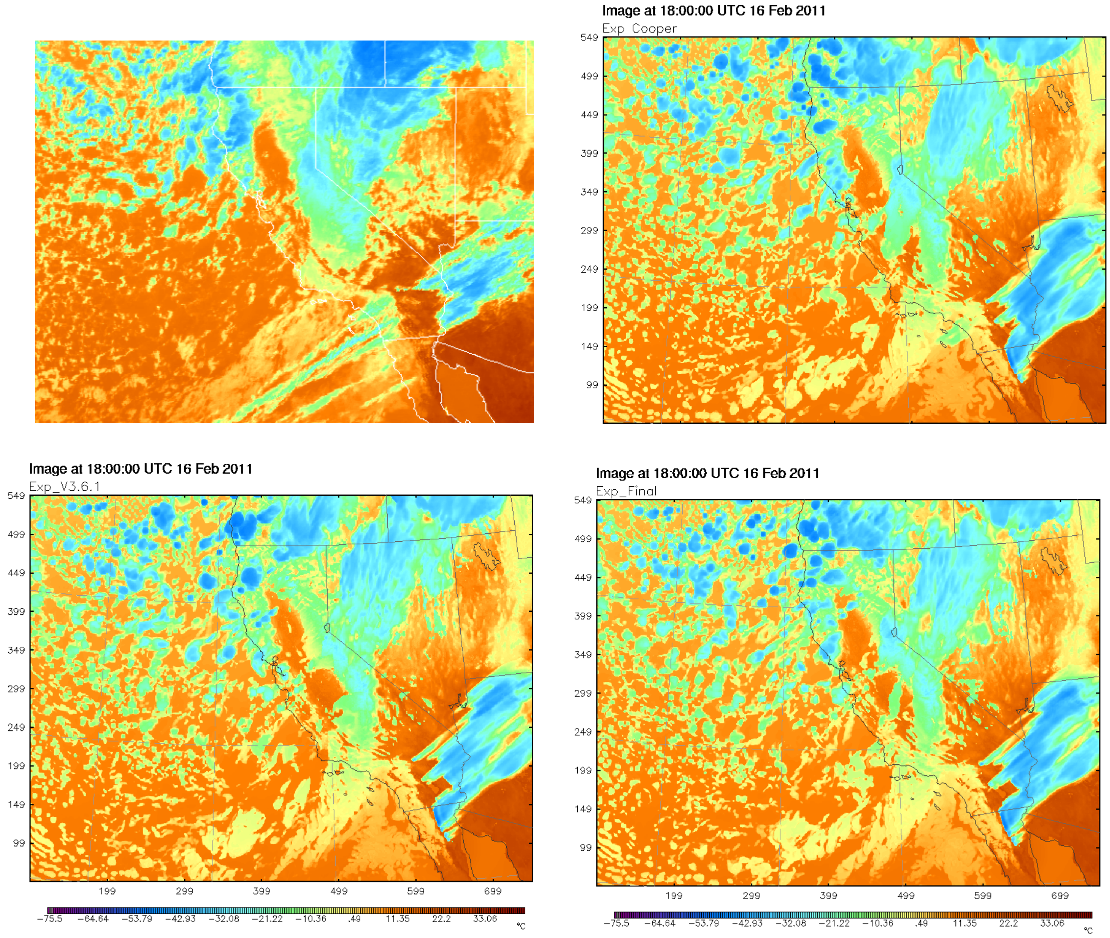

Figure A-4: Same as Figure A-1, 1800 UTC 16Feb 2011

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